

A coupled cartographic approach between bioclimatology and vegetation formations of Mexico

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Abstract

Aims: The task of classifying and naming Mexican vegetation types has been undertaken by previous botanists, ecologists, and mapping agencies. However, discrepancies remain due to the lack of criteria and joint efforts from a geographical and botanical perspective. We aim to unravel the complex interactions between climate and vegetation in Mexico using climatic data and advanced mapping techniques, display in maps the transition from land cover to vegetation maps and couple geobotanical and bioclimatological approaches to provide a sound, unified system for identifying Mexican bioclimatic physiognomic patterns. **Methods:** Bioclimatic mapping was developed from the Digital Climatic Atlas of Mexico data source. In addition, land cover and vegetation data were obtained from the National Institute of Statistics and Geography of Mexico regrouped as described by the Standardized Hierarchical Vegetation Classification. These data were analysed via standard map crossing technics using geographic information systems. **Results and conclusions:** The results revealed five ombrotypes and five thermotypes, leading to the identification of 13 different bioclimatic classes, which, when combined with physiognomic types, led us to recognize 11 forests, 3 shrublands and 3 herbaceous formations (at a scale of 1:4,000,000). The core outcome is a detailed bioclimatic/physiognomic vegetation map including forests, shrublands and areas dominated by Herbaceous/Non-Vascular formations. The map highlights the critical importance of harmonising methodologies to ensure comprehensive and accurate insights into Mexico's bioclimatic diversity.

Taxonomic reference: Villaseñor et al. (2005).

Syntaxonomic reference: Velázquez et al. (2021).

Abbreviations: INEGI = Instituto Nacional de Estadística y Geografía; SECLAVEMEX = Standardized Hierarchical Vegetation Classification; WBCS = Worldwide Bioclimatic Classification System.

Keywords

bioclimatology, geobotanical approach, land use, mapping techniques, Mexico, sustainable management, vegetation classification

Introduction

The study of vegetation, ranging from its traditional use in medicinal practices (Yuan et al. 2016; Khatoon Shaikh and Kanase 2022) to its contemporary applications such as carbon capture, disaster mitigation, and climate regulation, is gaining prominence (Fawzy et al. 2020). Traditional vegetation science, deeply rooted in ancient wisdom and practices, focuses on the responsible use of pristine ecosystems and the protection of biodiversity (Molnár and Babai 2021). On the other hand, modern vegetation science has transformed into a discipline focused on processes (Grime 2006), elucidating the mechanisms that govern species co-existence within plant communities (Saiz et al. 2016).

Over the past decade, we have witnessed the accumulation of vast amounts of information on vegetation. Nonetheless, data coverage and quality can vary significantly between regions, affecting the ability to fully classify vegetation types. Some countries, benefiting from initiatives such as the European Vegetation Archive database with its comprehensive data coverage, have been able to achieve more detailed classifications of vegetation types (Chytrý et al. 2016). However, not all countries have information that allows them to effectively apprehend this kind of information to classification systems to address the specific conditions unique to each country (De Cáceres et al. 2015). This challenge underscores the need for innovative proposals based on robust classification and syntaxonomical frameworks linked to new scientific advances such as bioclimatic approaches (Cano-Ortiz et al. 2022; del Río et al. 2024). As the study of vegetation evolves to encompass diverse aspects, it is imperative to advance our understanding and effectively combine the potential trends of vegetation in relation to climatic conditions (Afuye et al. 2021).

Bioclimatology: origin and outreach

Naturalists and scientists have long acknowledged the profound influence of climate on the distribution, behaviour, and adaptation of diverse species (Smit et al. 1996; Huey et al. 2012; Keenan 2015). Bioclimatology delves into the study of long-term weather patterns and its relation to biotic responses (Thompson and Perry 2013; Bonan 2015). Its origins trace back to early observations highlighting the intricate relationships between climate and living organisms. The establishment of bioclimatology as an independent discipline gained momentum in the 20th century, driven by technological advancements, refined data collection methods, and an escalating awareness of the effects of climate change (Rehfeldt et al. 2014a, 2014b; Heymann 2019).

Pioneers in this field, including notable scientists such as Alexander von Humboldt and Carl Troll, explored the intricate links between climate and vegetation (Holtmeier 2015; Hoorn et al. 2022). The development of climate classification systems, exemplified by the Köppen Climate Classification, further enriched our understanding of how various climates shape ecosystems and influence

the organisms found in specific regions (Lohmann et al. 1993; Beck et al. 2005). Bioclimatology, as an ecological discipline, meticulously explores the links between climatic conditions and the distribution of living organisms and vegetation patterns on a global scale. Salvador Rivas-Martínez contributed significantly to unravelling the relationship between climate and vegetation, developing the Worldwide Bioclimatic Classification System (WBCS) by connecting bioclimatic units to vegetation models and climate values (Rivas-Martínez et al. 2011). This enhanced understanding of vegetation distribution, coupled with changes in the structure and composition of potential vegetation, and allows scientists to identify critical bioclimatic thresholds for vegetation types. This is particularly crucial in addressing climate change concerns, where vegetation stands as both a prime indicator and a landscape component profoundly affected by environmental shifts.

Relevance of understanding vegetation patterns of megadiverse countries

The study of vegetation patterns is critical as nations grapple with imminent threats such as habitat loss, climate change, and resource overexploitation (Kumar and Verma 2017; Sáenz-Romero et al. 2020). Latin American countries such as Colombia, Bolivia, Peru, Brazil and Mexico exemplify high complexity due to their rich biodiversity and varied geophysical conditions (Rangel Churio et al. 1997; Navarro and Maldonado 2002; Ulloa Ulloa et al. 2017; Velázquez et al. 2021). Noteworthy classification initiatives in these nations employ both phytosociological and bioclimatic approaches. However, despite their significance, these initiatives fall short in providing comprehensive cartography that clarifies the intricate relationships between climate and vegetation. The study of plant formations in megadiverse countries stands at the forefront of scientific research, offering valuable insights into plant interactions, evolutionary processes, and ecological dynamics (Villaseñor et al. 2005; Carpio 2018; Hoveka et al. 2020). The approach of those studies not only enhance our scientific knowledge but also underscores the interconnectedness of ecological research and conservation efforts, emphasizing the importance of global collaboration in safeguarding the world's biodiversity.

Mexico is acknowledged as a megadiverse nation (Velázquez et al. 2021; Canet 2023), based on the criteria established by Mendoza-Ponce et al. (2020). In this regard, understanding the intricate vegetation patterns and biodiversity assumes paramount importance in addressing global challenges for biodiversity conservation. Moreover, vegetation patterns facilitate the identification of key habitats, biodiversity hotspots, and ecologically significant areas, forming the basis for targeted conservation strategies (Sloan et al. 2014; Topp and Loos 2019; Mendoza-Ponce et al. 2020). In addition to biodiversity conservation, a profound understanding of vegetation patterns plays a crucial role in climate resilience and adaptation efforts. These patterns serve

as indicators of climate change impacts, offering insights into plant species responses to environmental changes and guiding predictions and strategies for mitigation and adaptation (de Boer 1983; Wu et al. 2015; Afuye et al. 2021). The diverse vegetation in megadiverse regions also contributes significantly to ecosystem services, influencing water purification, pollination, climate regulation, and resource provision, thereby directly affecting human well-being on a global scale (Power 2010; Haines-Young and Potschin 2012).

Mexico holds extensive phytotaxonomic knowledge; however, it lacks a standardized phytosociological classification system that, on one hand, merges vegetation knowledge and, on the other, facilitates an understanding of its spatial distribution based on geobotanical standards (Pedrotti 2004; Mas et al. 2009; Velázquez et al. 2021). Over time, there have been attempts to fill this gap dating to the late 19th century with the works of Ramírez (1899), Harshberger (1911) and Ochoterena (1918; quoted by Velázquez et al. 2016) amongst others, each one contributing with formal maps delineating geobotanical regions in Mexico. In the latter stage of this progression, the vegetation classification system assumes a central role and starts to be integrated into cartographic legends. An example of this integration is found in the “Map of vegetation types of the Mexican Republic” by Flores Mata et al. (1971), with a scale of 1:2000,000. In this comprehensive work, the authors differentiate 25 types of vegetation, contributing to a more nuanced understanding of Mexico’s diverse botanical knowledge. These sequential efforts underscore the evolving nature of vegetation classification in Mexico, emphasizing the continuous refinement and integration of botanical knowledge into mapping frameworks.

Objectives

We pursue a dual objective, to both apply, for the first time (as far we know), a novel bioclimatic mapping methodology in Mexico, and to analyse its relationship with hierarchical land cover-vegetation physiognomic data. The newly mapped Mexican vegetation patterns are further discussed in terms of their relevance for predicting place-based climatic impacts on natural vegetation. This innovative approach allows for the prediction of site-specific bioclimatic patterns and vegetation physiognomy. This research represents a pioneering effort to integrate bioclimatic mapping with hierarchical land cover-vegetation physiognomy data in Mexico, highlighting its originality and contribution to the field of bioclimatic analysis and conservation planning.

Methods

Study area

Mexico, located in the southern region of North America, covers an area of approximately 1.96 million km², making it the third largest country in Latin America and the

fourteenth largest in the world (World Bank Group 2023). Bordered by the United States to the north, the country is flanked by the Pacific Ocean to the south and west, Guatemala, Belize and the Gulf of Mexico to the south-east, and the Caribbean Sea to the east. Mexico’s diverse geography encompasses a wide range of climates and geographical regions, from arid deserts to lush tropical rainforests. Moreover, the country is rich in biodiversity and has a varied topography, including mountains, plains, coastlines, and plateaus (Koleff et al. 2018; Alcocer and Aguilar-Sierra 2019). Mountain ranges such as the Sierra Madre Occidental and Oriental cross the country, influencing climate patterns, vegetation and contributing to the formation of distinct geographical regions. The convergence of the Nearctic and Neotropical biogeographic regions in Mexico creates a unique intersection of flora resulting in exceptional biodiversity (Silva-Flores et al. 2014; Sosa and Loera 2017).

Bioclimatic map of Mexico

In terms of bioclimatic cartography, our primary data source was the Digital Climatic Atlas of Mexico (DCAM). The atlas is mainly constructed from climatic data that include monthly and annual averages for precipitation and temperature from 1902 to 2011, obtained from the National Meteorological System (SMN) (Fernández Eguiarte et al. 2014). We followed the Gopar-Merino et al. (2015) methodology to analyse data from the DCAM. With the obtained precipitation and temperature data, several bioclimatic parameters and indices were calculated following the bioclimatic classification system proposed by Rivas-Martínez et al. (2011) (Table 1). The Rivas Martinez et al. (2011) classification system is based on:

- The close interrelationship between climate, vegetation, and geography, where there must be a relationship between bioclimate, vegetation series and biogeography. The bioclimate forms the basis of the system, the vegetation series comprises plant associations related to the same climax stage, and the “Telsela” serves as the basic unit of biogeography.
- Of particular importance in this system is the seasonality of precipitation, which refers to how it is distributed throughout the year. This, together with temperature and continentality, determines the existence of bioclimates (such as tropical pluvial, tropical pluvial-seasonal, etc.) within macrobioclimates.
- Continentality refers to the thermal amplitude and the difference between the months with the highest and lowest temperatures. Consideration of continentality is critical to the development of certain plant communities. This system nuances the existing vegetation responses within the same macrobioclimate, establishing a predictive and hierarchical bioclimatic typology.

Table 1. Bioclimatic parameters and indices as defined by Rivas-Martínez et al. (2011) and applied to the climatic data of the National Meteorological System for Mexico.

Abbreviation	Name	Definition
T	Annual Mean Temperature	Annual mean temperature in degrees Celsius (°C).
P	Annual Precipitation	Annual precipitation in millimetres (mm).
Pp	Positive Precipitation	Sum of the mean precipitation in millimetres for months with a mean temperature above 0°C.
Tp	Positive Temperature	Sum of temperatures for months with a mean temperature above 0°C, expressed in tenths of a degree.
Ic	Continentality Index	Expresses the difference or oscillation between the mean temperature of the warmest month (Tmax) and the coldest month of the year (Tmin). $Ic = Tmax - Tmin$.
It	Thermicity Index	The sum in tenths of a degree of the annual mean temperature (T), the mean temperature of the coldest month (m), and the mean temperature of the warmest month (M). It can also be calculated as the annual mean temperature plus twice the temperature of the coldest month, all multiplied by ten. It is an index that weighs the intensity of cold, a limiting factor for many plants and vegetal communities. $(T + M + m) * 10 \Leftrightarrow (Tmed + 2 * Tmin) * 10$.
Itc	Compensated Thermicity Index	An index that attempts to weigh the value of the thermicity index (It) due to the "excess" of cold or temperance that occurs during the cold season in continental or hyperoceanic territories on Earth. $Itc = It$ if Ic (8–18). They will be different if $Ic < 8$ or $Ic > 18$; then, a correction factor (Ci) must be calculated. If $Ic > 18$, then $Itc = It + Ci$. If $Ic < 8$, then $Itc = It - Ci$. Ci is a compensation factor calculated according to the proposal of Rivas-Martínez et al. (2011). This index allows the determination of the thermotype each of which can be differentiated into an upper and lower horizon.
Io	Annual Ombrothermic Index	This index is the ratio of Positive Precipitation (Pp) to Positive Temperature (Tp), multiplied by ten. $Io = (Pp / Tp) * 10$. This index allows the determination of the ombrotype. It can be differentiated into upper and lower horizons.
Iod ₂	Ombrothermic Index of the Dryest Bimonth	$Iod_2 = (Ppd_2 / Tpd_2)$. This index is derived from the total precipitation of the two driest months within the driest fourth-monthly period of the year (Ppd ₂), divided by the total temperature of the two driest months within the driest fourth-monthly period of the year (Tpd ₂).

The climatic units recognised in this system includes:

- Macrobioclimates, as the highest typological units, include Tropical (0–35° N-S), Mediterranean (23–52° N-S), Temperate (23–66° N-S), Boreal (42–72° N, 49–56° S) and Polar (53–90° N-S) regions. The basic unit is the bioclimate, of which there are 28 types. Bioclimatic variants allow for nuances within bioclimates. Within a bioclimate, we can specify the bioclimatic belt, which is determined by the combination of thermal (thermotype) and shading (ombrotype) components. Finally, by combining these bioclimatic factors as indices operating within an area, we have the isobioclimate. It is worth noting that mountainous areas are altitudinal variants of thermotypes and ombrotypes within a macrobioclimate.

The preliminary bioclimatic outcome depicted gradients of precipitation (ombro) and temperature (thermic) conditions clustered into bioclimatic patterns depicting all possible combinations of ombro and thermic indices. Due to scale issues, some of these bioclimatic classes were re-grouped on basis of their resemblance and correlation to the closely related adjacent index. This enabled us to construct a novel bioclimatic map of Mexico (*sensu* Gopar-Merino et al. 2015).

Vegetation physiognomic land cover map of Mexico

Cartographically, inputs were obtained from the National Institute of Statistics and Geography of México (scale 1:250,000; INEGI 2016, series VI). The vector input data were regrouped into two major cartographic classes, cultural and natural, as described by the Standardized Hierarchical Vegetation Classification (SECLAVEMEX) (Velázquez et al. 2016). To accomplish the objectives of this research, the vector layer map was reclassified into three classes of vegetation physiognomic categories using ArcMap GIS 10.5. The three classes were: forest (tree-dominated), shrubland (shrub-dominated), Herbaceous and Non-Vascular (herb-dominated) as described in Table 2. Water bodies and cultural land cover types were also depicted using data from Velazquez et al. (2021). We focused on a scale of 1:4,000,000 so that polygons smaller than 256 km² (< 4 mm² on the map) were merged with the adjacent larger polygon, taking the assigned category of that polygon.

Map crossing and correlation analyses

Mexican vegetation patterns were obtained by crossing the bioclimatic as well as the vegetation physiognomic land cover maps using ArcMap GIS 10.5. Correlations

among cartographic classes were used to either maintain or cluster classes accordingly to their climatic and physiognomic affinity. The complete methodological steps and the sources of information used to elaborate the core

product of the present research are presented in Figure 1. Actual surface in km² and in percentage values were computed to describe the final Mexican vegetation formation bioclimatic map.

Table 2. Description of vegetation physiognomic categories used for this survey. Tree (forests), shrub (shrublands), herbaceous and non-vascular plants (grasslands and Non-Vascular plants) categories are based on dominant attributes and specific growth forms and height characteristics. Dominant refers to life forms covering $\geq 60\%$ of the surface of the polygons (Velázquez et al. 2016, 2021).

Criteria	Dominant attributes	Qualifiers, definition and description of the dominant elements or attributes
Physiognomy (form of growth)	Tree	Forests. Dominated by woody-stemmed plants over 5 m tall.
	Shrub	Shrublands. Dominated by plants with one or more woody or succulent stems. Mostly less than 5 m tall or plants with arborescent or arborescent or arbofrutescent habit greater than 5 m tall.
	Herbaceous and Non-Vascular plants	Grassland. Dominated by plants without a woody base and Non-Vascular plants with no or primitive vascular system.

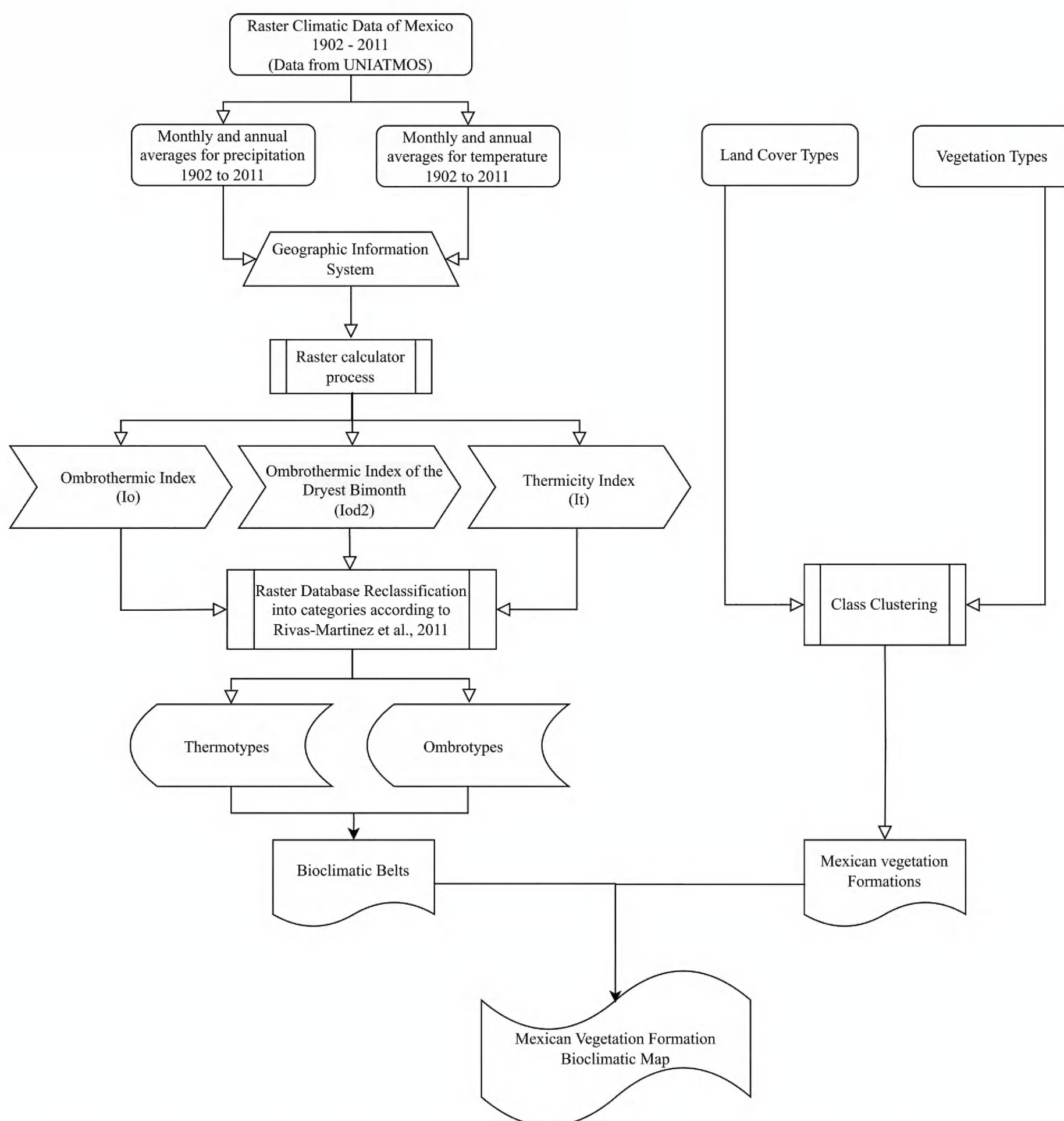


Figure 1. Flow chart illustrating step by step methods and the sources of information applied to compute the Mexican vegetation formation bioclimatic map (sources: INEGI 2016; Velázquez et al. 2016).

Results

Bioclimatic map of Mexico

Using climatic data as input, we showed five ombrotypes and five thermotypes as major bioclimatic classes of Mexico. The former includes (Hyper)Arid, (Semi)Arid, Subhumid, Humid, and Hyper-Ultra Humid precipitation classes, whereas the latter comprises Infra, Thermo, Meso, Supra and Oro tropical temperature classes. Arid ombrotypes cover 55.6%, whereas, Subhumid (29.8%) and Humid (13.8%) together cover 43% of the total surface of Mexico. However, the combination of these classes only permitted the cartographic expression of 13 bioclimatic classes. The dominant bioclimate in Mexico obtained was the (Semi)Arid Mesotropical (33.5% of the total Mexican surface). (Semi)Arid and Subhumid both Thermotropical bioclimate belts were the next best represented, 14.8% and 13.2% of the total Mexican surface, respectively (Table 3).

Distributions of the vegetation formations of Mexico

Within the Forest, the Infra-Thermo-Meso-Supratropical region covers 22,132 km² in (Hyper/Semi) Arid conditions and 134,085 km² in Dry environments. This is mainly containing spiny deciduous trees locally named Mezquital and partially, Deciduous Dry Forests. Infratropical areas show a shift from Subhumid to Humid climate areas (94,977 km²) with forests. This also comprises Deciduous broadleaved forest types intermingle with columnari- thorn forest life forms. The Thermotropical and the Mesotropical thermotypes show a spectrum from Subhumid to Humid ombrotypes, covering 328,002 km²; the former comprise Subdeciduous broad-leaved forests, and the latter are dominated by needle-leaved conifer forests. Supratropical Subhumid and humid forests cover 82,918 km², represent transitions that are mainly restricted to mountainous landscapes. The first contains an ecotone from Subdeciduous (Mainly broad-leaved) to Perennial (mainly scale and needle leaved) forests locally representing the Mexican timber line. The Orotropical Hyper-Ultra humid often represents evergreen perennial broad-leaved forests.

Shrublands, which predominate in the Dry Thermo-Meso-Supratropical zone, cover 532,521 km² and

represent a significant proportion of climates under water stress for long periods of the year. These shrublands include the Xerophitic shrubland that comprises a large number of vegetation communities such as Cardonal (dominated by *Pachycereus pringlei*), Tetetzal (*Neobuxbaumia tetetzo*), Izotal (*Yucca periculosa*), Nopaleras (*Opuntia* spp.), Magueyal (*Agave cupreata*, *A. durangensis*; *A. cerulata*), and arid sandy desert vegetation. One portion of these shrublands correspond mainly to the Mediterranean Macrobioclimate (158,117 km²); and this vegetation type is locally known as Chaparral shrublands (dominated by *Adenostoma*, *Arctostaphylos*, *Ceanothus*, *Quercus*, *Hechita*, and other genera) and is found in Baja California and expands largely into Chihuahua and isolated remnants in the central Plateau of Mexico. North American Chaparral is best represented in California and New Mexico states (Rivas-Martínez et al. 2011; González-Pérez et al. 2023).

The Herbaceous and Non-Vascular physiognomy is distributed in different bioclimatic belts spread over 84,862 km² in (Hyper/Semi) Arid and 80,616 km² are in the (Semi)Dry Infra-Thermo-Meso-Supratropical belts.

Water bodies, widespread across several bioclimatic levels, are critical for the maintenance of aquatic biodiversity and cover 12,958 km², while extensive human activities, land-use changes and urbanisation are reflected in the 529,794 km² of cultural areas (27.3%), which predominate in the (Semi)Dry Meso-Supratropical regions. This reveals the intricate ecological mosaic that characterises each physiognomic level across different climatic and geographical parameters. Cultural areas, prevalent in the (Semi)Dry Meso-Supratropical, indicate extensive human activities, land use change and urbanisation. Overall, the complex relationship of thermotypes, ombrotypes and vegetation physiognomic land cover types highlights the diverse ecological and bioclimatic belts of Mexico and emphasises the need for sustainable management and conservation efforts. Understanding these patterns is crucial for informed land management and conservation strategies.

The core output of the present research focuses on depicting specific regions where bioclimatic conditions may face changes. Figure 2 displays (at scale 1:4,000,000) 17 vegetation types, including the 11 forests, 3 shrubland and 3 herb-dominated ecosystems of the present Mexican vegetation physiognomy as depicted from climatic patterns. The 17 types are summarized as the legend of Figure 3.

Table 3. Data (percentage) depicting the 13 different bioclimatic belts of Mexico mappable at scale 1:4,000,000.

	Ombrotypes				TOTAL
	(Hiper)Arid	(Semi)Arid	Subhumid	Humid	Hiper-Ultra Humid
Infratropical			23.1	2.4	
Thermotropical	7.3	14.9	13.2	5.8	1.40
Mesotropical		33.5	6.6	3.4	
Supratropical			2.6	2.2	
Orotropical				0.0	
TOTAL	7.3	48.3	29.2	13.8	1.4

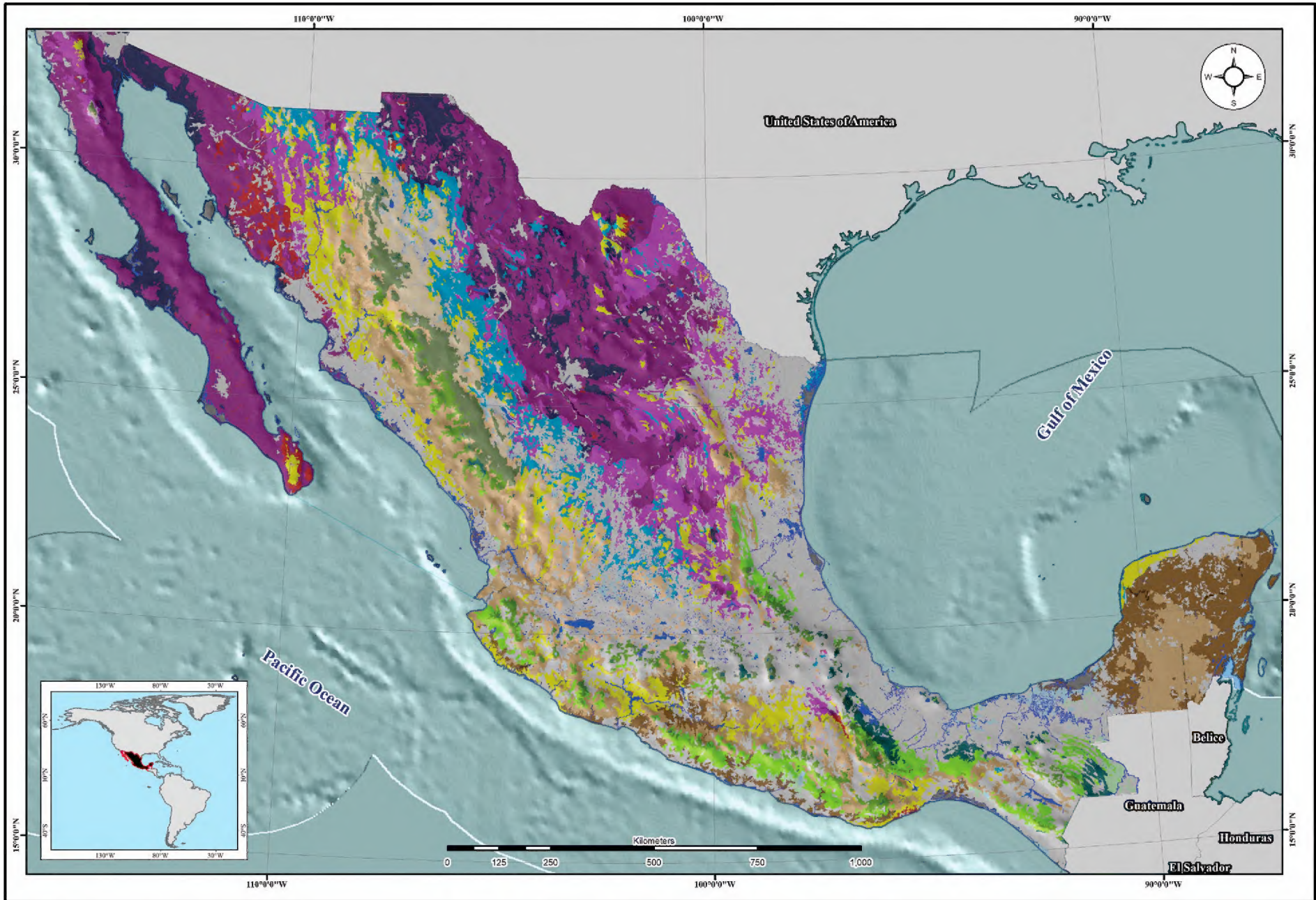


Figure 2. Vegetation pattern map of Mexico. On the whole, 17 native vegetation types, as a result of bioclimate and physiognomic land cover data crossing, were depicted.

Kilómetros cuadrados

Biomes	Termotypes	Ombrotypes						
		(Hiper/Semi) Arid	Dry	Subhumid	Humid	Hiper-Ultra Humid	(Sub) Humid	(Sub/Hiper/Ultra) Humid
Forest	Infra-Thermo-Meso-Supratropical	F1 (22,132)	F2 (134,085)					
	Infratropical			F3 (86,224)	F7 (8,753)			
	Thermotropical			F4 (156,727)	F8 (57,093)			
	Mesotropical			F5 (69,406)	F9 (44,776)			
	Supratropical			F6 (43,134)	F10 (39,784)			
	Infra-Thermo-Meso-Supra-Orotropical					F11 (15,768)		
Shrubland	Infra-Thermo-Meso-Supratropical	S1 (368,498)	S2 (158,117)					
	Thermo-Meso-Supratropical						S3 (6,047)	
Herbaceous and Non Vascular	Infra-Thermo-Meso-Supratropical	HNv1 (84,862)	HNv2 (80,616)					
	Infra-Thermo-Meso-Supra-Orotropical							HNv (20,316)
Water bodies		WB (12,958)						
Cultural		C (529,794)						

Figure 3. Legend of the vegetation pattern map of Mexico. Colours relate to map cartographic classes. Numbers in brackets correspond to km² covered by each class.

The forests corresponding to the hyper-arid and Semi-arid ombrotypes, with thermotypes ranging from infra to Supratropical in red, and the forests that thrive in the Dry ombrotype and in thermotypes ranging from infra to Supra-

tropical are in yellow. In the Sub-Humid ombrotype, forests range from Infra-tropical (brown) to Supra-tropical (cream) depending on the thermotype in which they develop. In the Humid ombrotype, forests develop from Infratropical (light

green) to Supratropical (army green). Forests developing in the Hyperhumid and Ultra-Humid ombrotypes are shown as dark green for all thermotypes. In the case of shrub formations, we have a range of purple colours. In Hyperarid and Semi-arid (including infra- to Supratropical thermotypes) the colour is purple. The shrubs found in the areas with dry ombrotypes in the infra- to Supratropical thermotypes are represented by a strong violet colour, and the formations that develop in the bioclimatic belt with sub-humid and humid ombrotypes in the Thermo-, Meso- and Supratropical thermotypes are defined by a soft violet colour. Finally, the category of Herbaceous and Non-vascular plants is represented by shades of blue; when they develop on bioclimatic belt with hyper-arid and semi-arid ombrotypes, with thermotypes ranging from infra- to Supratropical, we have defined them as dark blue. If they are found in the arid and thermotypes ranging from infra- to Supratropical, the colour assigned is intense blue, and finally, if we find elements of this category in the Sub-humid to Utra-Humid ombrotypes in all thermotypes (Infra-Orotropical), the colour assigned is light blue. Water bodies are shown in dark blue. Cultural areas are shown in grey. In the case of the forests, we find three different shades of colour. Vegetation communities nested within the native ecosystems described here are yet to be correlated at finer scales (e.g., 1:250,000) since spatially explicit floristic vegetation types are not yet available for the whole country (e.g., Velazquez et al. 2021).

Discussion

Bioclimatic map of Mexico

By using advanced bioclimatic and land cover mapping techniques, we are able to delineate the spatial distribution of different plant formation classes, providing insights into the extent and status of diverse ecosystems (Wolff et al. 2015; Velázquez et al. 2021; Sharma et al. 2022). This exploration of land cover patterns goes beyond mere cartography; it serves as a lens through which the transformation of ecosystems unfolds. This method has allowed us to illustrate vegetation physiognomy patterns in Mexico and explore their significance and relationships with bioclimate belts and vice versa.

Mapping the vegetation formations of Mexico is not novel. Ochoterena’s contribution (1937) offered a detailed description of the geographical distribution of plants in Mexico. This contribution includes rigorous floristic lists organized in a hierarchical classification system that spans from formations to “sinucias”, yet cartographic rigor was absent. Subsequently, the cartographic representation of Mexican vegetation gained prominence so that authors such as Dice (1943), Smith and Johnston (1945), Goldman and Moore (1946), and Leopold (1950), among others, made significant attempts. Climatic mapping efforts have been perhaps the most demanding and lagged behind other efforts. The outstanding work of Enriqueta García to adapt the Köppen climatic system to the Mexican conditions became a landmark (García 2004). García also produced a climatic zone map of Mexico at the scale of 1:500,000 containing three tropical, four dry, eight

temperate, and one polar group classes. These were further split into types, subtypes, and variables. The dominance of temperate group classes (inherited from the Köppen classification system) has always remained a major constraint in the Mexican transitional Nearctic-Neotropical context.

Our work highlights a number of key bioclimatic characteristics of Mexico. The dominance of Arid-(Humid)-(Thermo) Mesotropical types in the present bioclimatic map, covering 64.7% of Mexico’s surface area, reflects the ecological significance of these bioclimatic conditions, especially in Arid ombrotypes. Given global climatic trends, regions experiencing arid conditions may encounter challenges related to water scarcity and desertification. Conversely, shifts from Humid into Subhumid ombrotypes may be expected (Pontifes et al. 2018; Lee et al. 2021).

Vegetation formations of Mexico

The tabulated data provide a complex overview of the different physiognomic level and their respective thermotypes and ombrotypes, each making a distinctive contribution to the ecological mosaic (Figure 2). Currently, Mexico’s land has undergone anthropogenic change, with unprecedented agricultural and urban encroachment. Our present study reveals that 27.3% surface of the whole country is irreversibly changed into cultural land cover. Land cover types (cultural and water bodies) are misrepresented due to minimum cartographic area, so that small patches of crops were immersed into neighbouring vegetation formations (Table 4). The probable scenario of

Table 4. Dominant land cover and vegetation types clustered into the land cover physiognomic formations used in the present research. Vegetation types derived from polygons where taxonomic families, genus or species prevail combined with a specific phenology of the foliage (Velázquez et al. 2016). Physiognomic formations are distinguished by dominant life forms (INEGI 2016). A detailed and extended explanation and all vegetation types of Mexico and how they have been clustered into physiognomic formations may be found in Velázquez et al. (2016, Appendix A.8.).

Land cover classes and vegetation types	Land cover and Physiognomic formations
Towns	Cultural
Cities	
Cropland (irrigation & humid)	
Cropland (annual basis)	
Conifers	Forest
Conifers & broad-leaved	
Broad-leaved	
Mountain cloud forest	
Perennial & sub-perennial	
Deciduous & sub-deciduous	Shrubland
“Mezquital”	
Xerophytic scrubland	Grassland
Grassland	
Hygrophilous vegetation	Water bodies

small polygons merging into larger polygons jeopardizes 51% of the whole country to be converted into cultural within the years. Large polygons of native arid ecosystems are also threatened by global trends of climatic changes. The importance of comprehending present vegetation and land cover patterns stems from its far-reaching implications. Negative impacts on biodiversity, and alterations in hydrology and biogeochemical cycles are some of the already noticeable consequences (Rogé et al. 2014; Koleff et al. 2018;). Mapping these changes is essential for assessing and formulating land-use policies that compromise land use and conservation of native ecosystems. In the context of Mexico's megadiversity, vegetation mapping provides a platform for identifying and foreseen challenges and opportunities. Mapping provides a place-based platform for identifying and foreseen challenges and opportunities.

This study sheds light on the complex interplay between climate and vegetation in Mexico and highlights the central role of bioclimatology. The detailed bioclimatic and vegetation maps presented provide a comprehensive overview of the ecological mosaic, revealing the diverse bioclimatic conditions that characterise this megadiverse nation. However, it's important to recognise the limitations and perspectives of this comparison, especially when considering the broader context of biogeographic classifications. In addition, further research should consider other environmental factors such as soils.

The combination of bioclimatic data and vegetation maps reveals Mexico's ecological diversity, ranging from semi-arid to humid bioclimate, and from forest formations to shrublands. These findings underscore the complexity of Mexico's ecosystems and highlight the importance of sustainable management and informed conservation efforts.

Conclusion

The present survey provides a novel attempt to correlate bioclimatic classification data with physiognomic vegetation types of Mexico, as a long-term objective to delineate plant formations representing spatially explicit ecosystem

types. Detailed data on types within formation (e.g. order and alliances) and vegetation communities (associations) are yet to be compiled and analysed so that proper classification and cartographic analyses are simultaneously performed. Joint vegetation classification and climatic cartographic semi-detailed analyses are an important tool for biodiversity assessments but are rather limited, to our knowledge, in scientific literature. This is a core need in some megadiverse countries where biodiversity is rapidly vanishing, and environmental policies would benefit from geobotanical spatially explicit data.

Data availability

Bioclimatic data are available under request to the authors.

Author contributions

FG-M and AV led the contributions of all authors; FG-M performed bioclimatic, land cover and statistical and geographical analyses; AV conceived the research framework, collected data, performed statistical analyses, and wrote the paper; AGP performed statistical and bioclimatic geographical analyses; SRG conceived the research framework, and collected data; JFMC performed statistical and geographical analyses; AP collected data, performed botanical and statistical analyses.

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